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Applications of a cost-based method of excess air optimization for the improvement of thermal efficiency and environmental performance of steam boilers

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Abstract

The paper reviews the results of theoretical and experimental study on development and application of the method aimed at excess air optimization for utility/industrial steam boilers fired with fossil fuels. A concept of the cost-based excess air optimization is presented. Various application options (experimental/theoretical; firing different fossil fuels in utility/industrial boilers; pursuing distinct goals, etc.) are discussed. Three case studies including utility boilers firing lignite and fuel oil as well as an industrial boiler installed at a refinery are reviewed. Limitations and constraints in method application are discussed as well. As shown in this work, switching the combustion excess air to the optimized or "compromise" values ensures noticeable reduction of the total operational costs, associated with the fuel consumption ("internal" costs) and environmental impact ("external" costs), for the particular boiler.

Keywords: Fossil fuels; Excess air; Optimization model; Emission models; Fuel costs; Environmental costs

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Contents

1. Introduction

In most countries with a developing economy, power generation is generally based on firing fossil fuels of relatively low quality (e.g. lignite) and/or high-calorific fuels with elevated contents of fuel-S and fuel-N causing formation of harmful pollutants in combustion systems. Such a situation results in significant environmental impacts by the pollutants discharged from boilers of different power plants and industrial sectors via flue gas. Frequently, the utility and industrial enterprises experience a shortage of financial resources for fuel treatment as well as for installation of highly expensive gas-cleaning equipment (which would consequently increase the cost of electric and heat power production). Implementation of least-cost methods for the improvement of thermal

efficiency and environmental performance of operating power generating units seems, therefore, to be the most attractive way for energy conservation as well as mitigating environmental impacts by the electric and heat power producers.

One of the major requirements for the operation of utility and industrial boilers is to provide the highest possible thermal efficiency at a minimum impact on the environment. For a particular boiler, excess of combustion air (or excess air ratio, α) is the key operating variable affecting simultaneously the boiler's thermal efficiency, operational reliability and environmental performance (emissions from the unit) [1].

As known, in conventional combustion systems (widely employed in developing countries), with the diminishing of the excess of combustion air supplied to a fossil fuel-fired boiler, the rate of NO_x formation in the boiler furnace is basically lowered [2]. Reduced excess air also promotes lower SO_3 formation in high-temperature (post-flame) regions in the furnace. A quasi-linear proportional effect of the residual oxygen concentration (or, in effect, excess air) on the SO_3 emission from utility boilers firing high-sulfur fuel oil is confirmed experimentally [3]. Since SO_3 is formed due to oxidation of a small amount, up to a few percent, of sulfur dioxide [1], the SO_2 formation (and, consequently, emission) rate is, thus, weakly affected by excess air. Meanwhile, for low-sulfur fuels as well as for low-temperature combustion technologies, SO_2 formation is commonly assumed to be regardless of excess air.

However, at extremely low excess air ratios (less than the so-called "critical" excess air ratio, α_{cr}, generally depending on the fuel type and boiler load), CO is formed in the boiler furnace (in inverse proportion with excess air) indicating incomplete combustion in the boiler furnace and, therefore, leading to CO emission from the boiler. Accordingly, the rate of CO_2 formation for this range of the excess air ratio is slightly reduced because some amount of fuel-carbon is involved in CO formation. On the contrary, CO emission can be assumed to be negligible for sufficient air supply ($\alpha > \alpha_{cr}$). As the result, for the excess air values above 5–15% (lower limit corresponds to high-capacity units), the CO_2 emission rate becomes independent of the excess air ratio and is affected by the boiler fuel consumption and fuel-carbon only [4–6].

For the boiler performance, with the diminishing of excess air, the heat loss with the waste flue gas, q_2, becomes lower leading to the higher thermal efficiency of the boiler operation, i.e. to the fuel saving per unit electricity/heat production. However, the boiler operation at low excess air ratios ($\alpha > \alpha_{cr}$) is accompanied with elevated "combustion heat losses" which are associated with incomplete combustion, q_3, and unburned carbon, q_4 [1]. The heat loss q_3 points to the presence of some combustible gaseous species (CO, CH_4, H_2, etc.) in the flue gas leaving the boiler [7], whereas the heat loss q_4 is associated with carbon in fly and bottom ash (when firing coals) or soot and cenosphere particles carried out from the boiler by the flue gas (when firing fuel oil/gas) [8,9].

The formation of cenospheres is reported to be almost independent of combustion conditions, including excess air, and its rate is quite small [10]. That is why, the soot formation (caused by air deficiency in different zones of the diffusion flame) is basically taken into account when quantifying q_4 for fuel oil/gas-fuelled boilers and considered to be a source of particulate emissions from these units. As found experimentally, for firing either fuel oil or gaseous fuel (or when their co-firing), an increase in the excess air ratio in the region of $\alpha > \alpha_{cr}$ leads to the significant reduction in the boiler heat losses q_4 and q_3

[11]. However, for $\alpha > \alpha_{cr}$, the total sum of q_4 and q_3 for fuel oil/gas-fired boilers is rather small, almost independent of α, accounting for 0.1–0.5% (lower values correspond to high-capacity units) and, thus, negligible in the boiler heat balance for large boilers.

For boilers firing pulverized coals, the dependence of q_4 on α has a minimum at a certain excess air ratio (close to α_{cr}), and any deviation from the latter results in an increase in this heat loss [5,11]. Meanwhile, the q_3 values for coal-fuelled boilers are negligible because of the relatively large specified excess air ratios [1,5].

To gain the highest boiler thermal efficiency, the boiler heat losses must be minimized. For a fossil fuel-fired boiler, the total sum of the "combustion heat losses" and the heat loss with the waste flue gas is expected to have a minimum corresponding to the optimum excess air ratio. Such an approach is used in the conventional method of the excess air ratio optimization for utility and industrial boilers [11]. However, in this approach, the environmental impacts by the boilers are ignored when determining the optimum combustion conditions.

Apparently, the boiler heat losses cause "extra fuel" consumption, and the latter can be expressed as a cost parameter (with the use of the fuel price) and incorporated into "internal" boiler costs, i.e. associated with the boiler operation. Furthermore, the environmental impact of each gaseous/particulate pollutant emitted from the particular boiler, can also be estimated as a cost parameter and included into "external" boiler costs, inevitably paid for the damage done by the boiler unit to the environment and humans [12,13]. Minimization of the total costs comprising both the "extra fuel" costs and "external" costs is considered to be an objective function in the cost-based excess air optimization for the particular boiler [14, 15]. Advanced excess air optimization models combine the "external" costs together with "internal" costs accounting for the total fuel consumption by the boiler, thus, providing opportunities for the comparison of the fuel and "external" costs [4,6,16].

It should be noted that, because of some operating constraints, the specified (or actually applied on the operating boiler) excess air ratio may be slightly different from that obtained by the optimization model. Instead, "compromise" excess air (or "compromise" excess air ratio) can be applied for the improvement of the thermal efficiency and environmental performance of boilers [4,6,16].

This paper reviews various aspects and options in applications of the cost-based excess air optimization method to utility and industrial boilers fired with different fossil fuels. When reviewing three particular cases studies related to the boilers of different capacities, several objectives were pursued in this work: (1) to demonstrate the method flexibility with respect to the fuel type as well as the unit load; (2) to quantify various items of the "internal" and "external" costs; (3) to estimate economical benefits from switching the boilers to operation at the optimized (or "compromise") excess air ratio, etc.

2. Excess air optimization models

2.1. Objective functions

As reviewed above, the optimum excess air for the particular boiler can be obtained through different options leading to the minimized: (1) total excess-air-dependent heat

losses; (2) “internal” costs as “extra fuel” costs; (3) “internal” costs accounting for the boiler fuel consumption; (4) “external” costs accounting for the boiler environmental impacts; (5) combined, or total, “internal” and “external” costs. Accordingly, several objective functions can be used when determining the optimum excess air ratio.

2.1.1. Minimizing boiler total heat losses

For the particular boiler load, such an approach ensures the maximum boiler thermal efficiency corresponding to the optimum excess air ratio. However, the objective function may include the excess-air-dependent heat losses only: the heat loss owing to external convection and radiation, q_5, as well as that with bottom ash and slag, q_6, [1] can be omitted as independent of excess air. The objective function is then represented to be [5,11]

$$J_{\mathrm{hl}}(\alpha) = \mathrm{Min}(q_2 + q_3 + q_4). \tag{1}$$

As seen, the heat-loss-based method of the excess air optimization is quite simple and is associated with determining of the dependencies of q_2, q_3, and q_4 on α. However, the method is applicable for a single unit only and ignores the boiler environmental impacts. Besides, the method does not provide cost variables which could be taken into account when decision-making by the power plant management.

2.1.2. Minimizing “extra fuel” costs owing to excess-air-dependent heat losses

In this option, the objective function includes the “internal” cost variable (namely, the “extra fuel” costs, US\$/s, caused by the heat losses) to be minimized [14,15]:

$$J_{\mathrm{ef}}(\alpha) = \mathrm{Min}[10^{-2}(q_2 + q_3 + q_4)P_{\mathrm{f}}\dot{m}_{\mathrm{f,a}}] \tag{2}$$

where q_i is the relative heat losses, percent of the fuel lower heating value (LHV), for $i=2,3,4$; $\dot{m}_{\mathrm{f,a}}$ is the actual boiler fuel consumption, kg/s, accounting for fuel supplied to the boiler [1] and P_{f} is the fuel price, US\$/kg.

For a boiler, $\dot{m}_{\mathrm{f,a}}$ is determined for the current boiler load taking into account the input/output working fluid properties, LHV and boiler thermal efficiency, η_{b}, as affected by the above heat losses: q_2, q_3, q_4, q_5 and q_6 [1,11].

The simplicity as well as the feasibility of method application to the group of boiler units operated at different loads and/or fired with different fuels (with the aim of determining the optimum excess air ratio for each unit) are the main advantages of this optimization option. The model also provides potential savings of the fuel costs when switching the boiler to the operation with other excess air ratios, closer to the optimum excess air ratio. This option, however, is regardless of the boiler environmental impacts.

2.1.3. Minimizing fuel costs related to the boiler fuel consumption

For the opportunity of determining of both the total fuel costs and potential fuel savings for the particular unit, the objective function includes the boiler “internal” costs, US\$/s, found with the use of the actual fuel consumption by this boiler [4,6,16]:

$$J_{\mathrm{fc}}(\alpha) = \mathrm{Min}(P_{\mathrm{f}}\dot{m}_{\mathrm{f,a}}). \tag{3}$$

Actually, applications of the objective functions given by Eq. (2) or (3) lead to the same result in terms of the optimized excess air ratio; nevertheless, the latter option provides data for comparison of the total fuel costs with other relevant cost items as well as for estimation of the relative fuel cost savings.

The option is also applicable to the group of the boilers with corresponding representation of the objective function (via summing of the "internal" costs for all the boilers). However, this model has no concern related to the boiler environmental impacts.

2.1.4. Minimizing "external" costs related to the boiler environmental impacts

For this option, the "external" (or environmental) costs, US$/s, including effects of the excess-air-dependent emissions discharged from the studied boiler, are minimized [5]. The corresponding objective function for determining the optimum excess air ratio is thus given by:

$$J_{ec}(\alpha) = \mathrm{Min}(P_{NO_x}\dot{m}_{NO_x} + P_{SO_2}\dot{m}_{SO_2} + P_{SO_3}\dot{m}_{SO_3} + P_{CO_2}\dot{m}_{CO_2} + P_{CO}\dot{m}_{CO} + P_{soot}\dot{m}_{soot}) \quad (4)$$

where $\dot{m}$ is the emission rate of the "ith" pollutant, kg/s ($i=NO_x$ as NO_2, SO_2, SO_3, CO_2, CO and soot); P_i is the specific "external" cost, or cost of the damage done by 1 kg of the "ith" airborne pollutant, US$/kg [11,12].

For large utility and industrial boilers firing fuel oil/gas at relatively low excess air, the rate of soot formation is reported to be rather low because of an effect of the furnace residence time [8]. In the coal-fired boilers, the soot formation is negligible because of sufficient air supply. Taking these facts into account, as well as the relatively low value of P_{soot} [12], the last term in Eq. (4) can be omitted, and the objective function includes the effects of the gaseous emissions only.

For this optimization option, the knowledge of the boiler fuel consumption affecting the emission rates is required. However, the model does not include the "internal" boiler costs and, thus, is limited by the environmental impacts only.

When necessary, the above objective function can be applied to the group of the boiler units operated at different loads and/or fired with different fuels (accounting for the overall environmental impact by the selected boiler units).

2.1.5. Minimizing total fuel and "external" costs

In this option, which seems to be the general one in this cost-based optimization method, the "internal" (or fuel) costs are combined in the objective function with the "external" (or environmental) costs. Ignoring an impact caused by the soot particles, the total costs, US$/s, can be minimized with the use of the following objective function [4,6,16]:

$$J_{tc}(\alpha) = \mathrm{Min}(P_f\dot{m}_{f,a} + P_{NO_x}\dot{m}_{NO_x} + P_{SO_2}\dot{m}_{SO_2} + P_{SO_3}\dot{m}_{SO_3} + P_{CO_2}\dot{m}_{CO_2} + P_{CO}\dot{m}_{CO}). \quad (5)$$

The above model is applicable in both experimental and theoretical investigations aimed at the determining of the optimum operating conditions for the individual boiler or for the group of boiler units.

Apparently, the experimental approach in the excess air optimization ensures more reliable results. However, in the experimental tests, especially on the coal-fired boilers, the unit load may significantly fluctuate responding to various external (e.g. related to the power demand) and internal (e.g. associated with fuel quality) disturbances. Accordingly, the boiler fuel consumption is randomly varied around the "set point". To avoid an effect of these time-domain fluctuations on the optimization process, in the above models, one can use the "specific" characteristics (i.e. per kWh of the energy produced) rather than the absolute mass flow rates: for the fuel consumption, emissions and cost variables [5].

The theoretical approach, or modeling, is important in the boiler design as well as when boiler retrofitting and/or switching to other fuel option.

Meanwhile, for all the applied approaches, the operating constraints must be taken into account which may result in the selection of the "compromise", rather than optimized, excess air ratio [4,6,16].

2.2. Emissions

2.2.1. Determining the emission rates in an experimental study

For NO_x, (as NO_2), SO_2, SO_3, CO and CO_2, the emission rates, kg/s, are determined taking into account measured emission concentrations of the pollutants, ppm, in the dry flue gas at sampling point

$$\dot{m}_{NO_x} = 2.05 \times 10^{-6} \dot{m}_f NO_x V_{dg} \tag{6}$$

$$\dot{m}_{SO_2} = 2.93 \times 10^{-6} \dot{m}_f SO_2 V_{dg} \tag{7}$$

$$\dot{m}_{SO_3} = 3.57 \times 10^{-6} \dot{m}_f SO_3 V_{dg} \tag{8}$$

$$\dot{m}_{CO} = 1.25 \times 10^{-6} \dot{m}_f CO V_{dg} \tag{9}$$

$$\dot{m}_{CO_2} = 1.98 \times 10^{-6} \dot{m}_f CO_2 V_{dg} \tag{10}$$

where $\dot{m}_f$ is rated fuel consumption, kg/s, i.e. related to fuel burned out in the boiler [1]; for high-volatile coals and fuel oil/gas one can assume $\dot{m}_f = \dot{m}_{f,a}$; V_{dg} is volume of dry flue gas (under standard conditions) per unit fuel mass, m^3/kg, at the sampling point.

Actually, V_{dg} is the function of the excess air ratio at the sampling point as well as of the fuel analysis and is generally found for complete combustion of the fuel [1,11]. However, in rough calculations, V_{dg} can be approximated by [11]:

$$V_{dg} \approx \alpha_{sp} V^0 \tag{11}$$

where V^0 is theoretical volume of air (under standard conditions) required for complete combustion of 1 kg fuel, m^3/kg; α_{sp} is actual excess air ratio quantified with the use of the O_2 concentration, %vol., in the dry flue gas at the sampling point [7,11].

Like V_{dg}, V^0 is readily determined with the use of the fuel properties [1,11]. However, when the fuel composition is not available, the V^0 value can be found from

its statistical correlation with LHV [4,11] providing the opportunity for the estimation of V_{dg} as well.

Alternatively, the rate of carbon dioxide emission from a boiler firing high-volatile coal or fuel oil, kg/s, can be predicted without needs of determining the CO_2 concentration in the flue gas ignoring, however, the CO formation [4–6]:

$$\dot{m}_{CO_2} = 0.03667\dot{m}_f C^r \tag{12}$$

where C^r is carbon content, %wt, in the "as-received" fuel analysis.

Such an approach ensures higher accuracy in the determining of $\dot{m}_{CO_2}$ When the fuel analysis is not available, the carbon content can be estimated from its statistical correlation with LHV [4,11] for the particular fuel.

For complete combustion of fuel gas, when the fuel properties are available, the CO_2 emission rate, kg/s, can be determined more accurately by [17]:

$$\dot{m}_{CO_2} = 0.0198\dot{m}_f(CO_2 + CO + CH_4 + 2C_2H_6 + 3C_3H_8 + 4C_4H_{10} + 5C_5H_{12})/\rho_{fg} \tag{13}$$

where ρ_{fg} is density of fuel gas (under standard conditions), kg/m^3; and the gas concentrations, %vol., in Eq. (13) represent the fuel gas analysis.

2.2.2. Modeling the gaseous emissions

In the computational study, input data for modeling the gaseous emissions from the studied boiler should include the fuel analysis together with the boiler thermal and geometrical characteristics.

The models for the determining of emission concentrations of the acid rain pollutants (NO_x, SO_2 and SO_3) in flue gas are proposed in Ref. [17] based on the assumption of considering a burner zone in the boiler furnace as a control volume.

For carbonaceous oxides, the CO emission rate is estimated with the use of a semi-empirical model, whereas CO_2 emission rate is basically predicted with the use of the fuel analysis [4,6,16].

Conventionally, the burner zone includes the part of the furnace volume confined by the furnace water walls and, also, by two horizontal planes, located at 1.5 m above and 1.5 m below the burners, and the distance between these planes is referred to as the burner zone height [18].

2.2.2.1. NO_x emissions. For the NO_x emissions from conventional combustion of fossil fuels, the model includes the contributions by thermal, fuel and prompt NO_x. The thermal NO_x are generally formed from nitrogen of air in the post-flame region under high-temperature conditions [17,19] and obviously affected by the residual (or excess) oxygen concentration, kg/m^3, the latter being found by [17]

$$C_{O_2} = 0.21\rho_{O_2}V^0[(\alpha_{bz} - 1) + r(\alpha_{rg} - \alpha_{bz})]/V_{wg} \tag{14}$$

where ρ_{O_2} is density of oxygen (under standard conditions), kg/m^3 ($\rho_{O_2} = 1.428$ kg/m^3); α_{bz}, α_{rg} are excess air ratios for the burner zone and for the (wet) flue gas recirculated into

the furnace, respectively; r is fraction of the recirculated flue gas (basically, taken off from the boiler economizer exit) and V_{wg} is volume of wet flue gas (under standard conditions), m^3/kg, formed in complete combustion of 1 kg fuel in the burner zone, including gas recirculation [1,11].

As seen in Eq. (14), the flue gas recirculation (basically, used for reducing the flame temperature in the burner zone as well as for controlling superheat and reheat steam temperatures) has a noticeable influence on the C_{O_2} and, consequently, thermal NO_x emissions. The flue gas recirculation technique is generally applied on fuel oil/gas-fired boilers and, in some cases, on coal-fired boilers, e.g. when firing high-moisture lignite [3].

The second important factor involved in the NO_x emission model is the maximum (or effective) temperature in the burner zone calculated by:

$$T_m = \beta_{bz} T_a^* (1 - \psi_{bz})^{0.25} (1 - r^{1+nr}) m_b \tag{15}$$

where β_{bz} is fraction of fuel actually burned out in the burner zone [17,18,20]; T_a^* is conventional adiabatic temperature, K, found with ignorance of the effect of flue gas recirculation [17]; ψ_{bz} is coefficient of thermal efficiency averaged over the surfaces "covering" the burner zone [1,18]; n, m_b are empirical factors accounting for the effects of the gas recirculation method and the burner type [17].

For all the fossil fuels, the concentration of thermal NO_x (as NO_2, under standard conditions) in the wet flue gas downstream from the furnace of the 100% loaded boiler, g/m^3, can be found by a single model:

$$C_{NO_2^{th}} = 7.03 \times 10^3 C_{O_2}^{0.5} t \exp(-10860/T_m) \tag{16}$$

where t is relative time factor, including an effect of the residence time [17].

As seen, by a structure, Eq. (16) is similar to Zeldovich Equation for estimating thermal NO formation in a well-stirred reactor [21]. The variables included in Eq. (16) are strongly affected by the boiler operating conditions as well as by the furnace geometrical and thermal characteristics.

Despite different sources of the fuel and prompt NO_x formations (from fuel-N and nitrogen of air, respectively), there are some compounds common for the both formation mechanisms, such as HCN and NH, basically produced in the flames zone and further oxidized to NO in the post-flame region at presence of excess air [19], which are responsible for the fuel and prompt NO_x emissions.

For a 100%-loaded boiler firing coal or fuel oil, the total concentration of fuel and prompt NO_x (as NO_2, under standard conditions) in the wet flue gas at the furnace exit, g/m^3, is predicted depending on the T_m level to be [17]:

– for the temperatures of $2100 > T_m \geq 1850$ K:

$$C_{NO_2^{f+p}} = (0.4 - 0.1\mathrm{N^r})\mathrm{N^r}[(\alpha_{bz} + r)/(1 + r)]^2 \times [(2100 - T_m)/125]^{0.33} \tag{17}$$

– for the temperatures of $1850 > T_m \geq 800$ K:

$$C_{NO_2^{f+p}} = 1.25(0.4 - 0.1N^r)N^r[(\alpha_{bz} + r)/(1 + r)]^2 \times [(T_m - 800)/1000]^{0.33} \quad (18)$$

where N^r is nitrogen content in fuel "as-received", %wt.

For firing fuel gas, there is no the contribution of fuel NO_x, and the concentration of prompt NO_x (as NO_2, under standard conditions) in the wet flue gas at the furnace exit of a 100%-loaded boiler, g/m^3, is found by [17]:

$$C_{NO_2^p} = 0.1[(\alpha_{bz} + r)/(1 + r)]^2 \times [(1.01T_m - 800)/1000]^{0.33}. \quad (19)$$

For the boiler operated at any arbitrary load, the total NO_x (as NO_2) emission concentration in the wet flue gas at the furnace exit, g/m^3, is calculated to be [17]:

– for firing coal and fuel oil:

$$C_{NO_2} = C_{NO_2^{th}}(N/N_0) + C_{NO_2^{f+p}}(N/N_0)^{0.5}, \quad (20)$$

– for firing fuel gas:

$$C_{NO_2} = C_{NO_2^{th}}(N/N_0) + C_{NO_2^p}(N/N_0)^{0.5} \quad (21)$$

where N/N_0 is relative boiler load, i.e. related to the 100% boiler load, N_0.

Finally, the predicted (uncontrolled) NO_x emission rate is determined by:

$$\dot{m}_{NO_x} = 10^{-3}\dot{m}_f C_{NO_2} V_{wg}. \quad (22)$$

Note that the excess air ratio, α, is generally specified for the furnace exit ($\alpha = \alpha_f$) [1,11].

Accordingly, the excess air optimization can be applied to α_f. The values of α_{sp}, α_{bz} and α_{rg} in Eqs. (11), (14), (17) and (19) are then estimated with the use of the leakages from the ambient air into the flue gas path for different boiler heating surfaces [11,18]. It should also be noted that with the simultaneous use of two types of the gas recirculation (involving "hot" and "cold" flue gases), the above model might be correspondingly modified [22,23].

As may be seen, the model for predicting NO_x emissions is quite sensitive to the operating conditions, specifically to the temperature in the burner zone. In turn, the temperature level is affected by the fuel properties and burnout rate as well as by the excess air ratio, flue gas recirculation and the boiler furnace design. In order to ensure reliable predicted results, the NO_x emission models were validated in various case studies [22–25].

2.2.2.2. SO_3 and SO_2 emissions. Similar to NO_x, SO_3 is basically formed in the post-flame zone under high-temperature conditions at presence of excess air. As found experimentally, the SO_3 formation is almost independent of the flue gas recirculation [3]; that is why, r is not present in the SO_3 emission model. The volume O_2 concentration, %vol., used in the SO_3 emission modeling (instead of the mass oxygen concentration,

C_{O_2}), is estimated to be:

$$O_2 = 21(\alpha_{bz} - 1)V^0/V_{wg}. \tag{23}$$

Since SO_3 is formed from SO_2, the yield of SO_3 depends on the volume fraction of SO_2 in the wet flue gas, the latter being found by [17]:

$$p_{SO_2} = 0.007S^r/V_{wg} \tag{24}$$

where S^r is sulfur content, %wt, in the "as-received" fuel analysis.

In this model, the effect of the temperature is used indirectly, through the furnace "heat load". The SO_3 concentration in wet flue gas (under standard conditions) at the furnace exit, g/m^3, is then predicted to be [17]

$$C_{SO_3} = 0.01514p_{SO_2}(O_2)^{0.5}q_f(N/N_0)^2 \tag{25}$$

where q_f is heat release rate per unit furnace cross-sectional area, kW/m^2.

As seen in Eq. (25), the SO_3 concentration in the flue gas is proportionally dependent on the SO_2 formation (or fuel-S) and is affected by both the boiler load and excess air in the burner zone. Accordingly, with higher SO_3 formation, the SO_2 concentration, g/m^3, in the wet flue gas (under standard conditions) at the furnace exit becomes somewhat lower [16]:

$$C_{SO_2} = 2.86(1000p_{SO_2} - 0.28C_{SO_3}). \tag{26}$$

Thus, the models for SO_3 and SO_2 formations include the effects of the load and excess air ratio. However, the models are regardless of the flue gas recirculation.

The SO_3 concentration in the flue gas is reported to be relatively small, of 5–50 ppm [1]. Mostly, SO_3 formation is considerable in the boilers firing medium- and high-sulfur fuel oils because of elevated p_{SO_2} and q_f, (despite relatively low excess air). For other fuels (low-sulfur fuel oil, fuel gas and coals with moderate and low sulfur contents), this pollutant can be excluded from the excess air optimization model. Moreover, when firing coals, a noticeable amount of SO_3 is consumed in formation of sulfates (via reactions with sodium and potassium of fuel) as well as in corrosion processes, both occurring in the boiler furnace, which results in the reduction of SO_3 emission [1] and justifies the ignorance of this pollutant in the model for coal-fired boilers.

Thus, the predicted rates of uncontrolled SO_3 and SO_2 emissions from a boiler firing fuel oil are found, respectively, by

$$\dot{m}_{SO_3} = 10^{-3}\dot{m}_f C_{SO_3} V_{wg} \tag{27}$$

$$\dot{m}_{SO_2} = 10^{-3}\dot{m}_f C_{SO_2} V_{wg}. \tag{28}$$

For the boiler unit equipped with the flue gas desulfurization (FGD) system of efficiency η_{FGD}, the above values of $\dot{m}_{SO_3}$ and $\dot{m}_{SO_2}$ should be multiplied by $(1-\eta_{FGD})$ when determining the actual emission rates of SO_3 and SO_2.

For coal-fuelled boilers, the rate of SO_2 formation depends on fuel-S and the boiler fuel consumption only (assuming zero SO_3 formation) and, like CO_2, is independent of the excess air ratio. However, when firing coals, some part of SO_2 (in the presence of water

vapor in the flue gas) is absorbed by fly ash while ash particles pass through boiler gas ducts [26], thus, leading to the reduced SO_2 emission from the boiler. The rate of "in-boiler" FGD depends mainly on the CaO/S^r molar ratio. In this ratio, CaO, %wt, is referred to as the calcium oxide content in the fuel mass "as-received" and is estimated to be:

$$\mathrm{CaO} = 0.01\mathrm{A}^{\mathrm{r}}\mathrm{CaO}^{\mathrm{ash}} \tag{29}$$

where A^r is ash content, %wt, in the "as-received" fuel analysis and $\mathrm{CaO}^{\mathrm{ash}}$ is content of CaO, %wt, in fly ash.

As proposed in Ref. [23], the rate of "in-boiler" FGD can be approximated by:

$$K_{\mathrm{SO_2}} = 0.21(a_{\mathrm{c}}\mathrm{CaO/S^r})^{0.5} \tag{30}$$

where a_c is mass fraction of fly ash (normally, 0.9–0.95 for dry-bottom boiler furnaces [11]).

For a coal-fired boiler unit equipped with the FGD system of efficiency η_{FGD}, the emission rate of SO_2, kg/s, is found taking into account the effects of both $K_{\mathrm{SO_2}}$ and η_{FGD} to be:

$$\dot{m}_{\mathrm{SO_2}} = 0.02(1 - K_{\mathrm{SO_2}})(1 - \eta_{\mathrm{FGD}})\dot{m}_{\mathrm{f}}\mathrm{S^r}. \tag{31}$$

When firing fuel gas, small amounts of SO_3 and SO_2 may be produced in the boiler furnace because of possible presence of H_2S in fuel gas. Normally, these values are negligible and, therefore, can be omitted in the computational model.

2.2.2.3. CO and CO_2 emissions. Despite a relatively small rate, the CO emission plays an essential role in the excess air optimization, affecting the region of the low excess air ratios. However, the models directly accounting for the effects of the boiler operating conditions on CO formation in the fossil fuel-fired furnace do not exist.

Based on the analysis of experimental data on carbon monoxide emission from fuel oil/gas-fired boilers, the correlation between the volume CO concentration in dry flue gas, %vol., and the furnace excess air ratio ($\alpha = \alpha_f$) was proposed in Refs. [4,6]. In this empirical model, the CO formation is calculated for the two excess air ratio ranges to be:

– for the range of $1.0 < \alpha < \alpha_{cr}$

$$\mathrm{CO} = A(\alpha_{\mathrm{cr}} - \alpha)^2 \tag{32}$$

– for the range of $\alpha \geq \alpha_{cr}$:

$$\mathrm{CO} \approx 0 \tag{33}$$

where A is empirical factor.

The critical excess air ratio, α_{cr}, as well as the factor A are found experimentally. However, in rough calculations related to fuel oil/gas-fired boilers, α_{cr} can be assumed to be 1.03–1.04 for high-capacity boilers [3,4] and up to 1.15–1.20 for small- and medium-size industrial units, while $A = 50$ is appropriate for wide ranges of the boiler capacity and load [4,27].

The above CO emission empirical model seems to be also applicable for the large coal-fired boilers with expected values of $\alpha_{cr}=1.15$–1.25 (the lower limit corresponds to high-volatile coals, e.g. lignites [5]). For small- and medium-size industrial boilers, the α_{cr} values should be assumed based on the statistical data on the boiler performance tests.

With the available fuel analyses, the CO_2 emission rate is predicted by Eqs. (12) and (13) for the boilers firing distinct fuels. For the range of $1.0<\alpha<\alpha_{cr}$, the amount of carbon involved in CO formation is quite small and can be neglected in calculation of the CO_2 emission rate.

2.3. Excess-air-dependent heat losses

The heat losses q_2, q_3 and q_4 are important variables in the excess air optimization because their values are strongly affected by α. In the experimental study, these losses are found with the use of common methods employed in the boiler performance tests, based on the collected data including relevant operating variables and fuel properties [7,11].

In the computational study of coal-fired boilers, the heat loss owing to unburned carbon, percent of the total heat input to the boiler, can be estimated by the empirical model [28] which includes the effects of fuel properties and characteristics as well as the excess air ratio at the burner zone:

$$q_4 = 0.52 C_f C_b C_{sr}[1.5 + C_a(\delta\alpha)^{1.2}](A^r R_{90})^{0.9}/(V^{daf})^{1.5} \tag{34}$$

where R_{90} is pulverized fuel fineness, %; V^{daf} is percentage of the volatile matter in the dry and ash-free fuel analysis, %wt; C_f is fuel grade factor ($C_f=0.5$ for anthracites, for other coals $C_f=1$); C_b is burner factor ($C_b=1$ for swirl-type burners; for straight-flow burners $C_b=1.2$); C_{sr} is ash removal factor ($C_{sr}=1$ for dry bottom- and $C_{sr}=0.5$ for slag-tap-furnaces).

The parameters $\delta\alpha$ and C_a in Eq. (34) depend on the relationship between α_{bz} and α_{cr} (the latter is assumed to be very close to the excess air ratio corresponding to the minimum q_4)

– for $\alpha_{bz}<\alpha_{cr}$: $\delta\alpha=\alpha_{cr}-\alpha_{bz}$ and $C_a=35$
– for $\alpha_{bz}\geq\alpha_{cr}$: $\delta\alpha=\alpha_{bz}-\alpha_{cr}$ and $C_a=5$.

For fuel oil/gas-fired boilers, as is shown in Ref. [3] for the range of $1.0<\alpha<\alpha_{cr}$, there is a certain correlation between q_4 and q_3, represented by a simple approximation [16], which can be used in the computational study:

$$q_4 \approx 0.15 q_3. \tag{35}$$

The heat loss owing to incomplete combustion is calculated following the general methodology for determining of q_3 [1,7]. Taking into account the percentage of the volume carbon monoxide concentration by Eqs. (32) and (33) and neglecting the hydrogen and methane concentrations in the flue gas, this heat loss, percent of the total heat input to the boiler, for a boiler fired with an arbitrary fossil fuel is found to be [1]

$$q_3 = 126.4\,\mathrm{CO}\,V_{dg}(100 - q_4)/Q_{av} \tag{36}$$

where Q_{av} is total heat input, kJ/kg ($Q_{av}\approx$ LHV).

As seen, for firing fuel oil/gas at $1.0<\alpha<\alpha_{cr}$, Eq. (36) includes q_4 determined by Eq. (35), i.e. with the use of q_3. So, the trial-and-error method should be involved in the determining both heat losses for the fuel oil/gas-fired boilers operated at extremely low excess air ratios.

The heat loss with the waste flue gas, percent of the total heat input to the boiler, is calculated to be [1]:

$$q_2 = (H_{wg} - \alpha_{wg}H_a)(100 - q_4)/Q_{av} \quad (37)$$

where H_{wg} is enthalpy of the waste flue gas (at the boiler air heater exit), kJ/kg; H_a is enthalpy of air under ambient conditions, kJ/kg, and α_{wg} is excess air ratio for the waste flue gas.

With the increasing of the excess air ratio in the furnace (and, accordingly, in the waste gas at the boiler exit), the waste gas temperature is somewhat reduced affecting H_{wg} [3,5]. That is why, in the theoretical approach, the use of the correlation between the waste gas temperature and α_{wg} would lead to the more accurate computational results.

3. Case studies

3.1. Firing Thai lignite in a 150 MW utility boiler

3.1.1. Boiler design characteristics

In this experimental study [5], a 150 MW boiler firing Thai lignite was selected for the excess air optimization. At the rated capacity (100% load), the boiler produced some 120 kg/s of superheated steam at 535 °C and 140 bar. The reheated steam of about 110 kg/s at 34 bar was returned to the boiler with the aim to increase its temperature to 535 °C.

The tangentially-fired boiler furnace (13.03×10.64 m^2), with the burners arranged at four corners, ensured conventional combustion of pulverized Thai lignite. The rated heat release rate of the furnace (per unit cross-sectional area) was about 2.7 MW/m^2 when firing lignite with the LHV of 10 MJ/kg. For the 100% boiler load, the excess air ratio at the furnace outlet was specified at the value of 1.28 (similar to that at the economizer exit).

3.1.2. Fuel properties, major operating variables and emission concentrations

For determining the thermal and environmental boiler characteristics, the experimental tests were conducted at full boiler load for five different values of the excess air ratio by maintaining the excess oxygen concentration at the economizer exit. During a single test, the boiler characteristics were fluctuated and, therefore, were averaged (over time).

Table 1 shows actual fuel properties whereas Table 2 provides the major boiler operating variables as well as the measured emissions for all the tests. As seen, during this 8-h boiler testing, there were noticeable variations of the fuel properties and the unit power output (despite it was controlled and maintained at constant value), the latter being mainly affected by the fluctuations in the fuel quality and electric power demand.

For obtaining the emission concentrations, the flue gas was sampled at the economizer exit (for NO_x and CO) as well as at the FGD unit exit (for SO_2). In addition, the contents of

Table 1
Properties (%wt) and LHV (MJ/kg) of Thai lignite ("as-received" basis) fired in the 150 MW boiler during the experimental tests [5]

Run no.	W^r	A^r	C^r	H^r	O^r	N^r	S^r	LHV
1	33.30	20.18	33.07	0.63	9.34	1.23	2.25	10.25
2	32.50	20.75	33.11	0.76	9.18	1.32	2.38	10.45
3	30.70	22.32	33.35	0.66	9.24	1.31	2.42	10.47
4	34.50	18.38	33.12	0.49	9.82	1.28	2.41	10.06
5	33.90	19.34	32.17	0.67	10.39	1.23	2.30	9.86

unburned carbon in fly ash (essential in quantifying of q_4) were determined in the laboratory analyses for each test run.

As seen in Table 2, with the increasing of excess oxygen (or excess air ratio), the NO_x emission concentrations in the 6% O_2 fuel gas were increased indicating the domination of the fuel-NO_x emission mechanism [29]. Meanwhile, the SO_2 concentrations in the flow gas downstream from the FGD units were at relatively small values corresponding to the combined effects of the "in-boiler" SO_2 reduction and the high-efficiency (97.5–98.5% for distinct test runs) FGD system. The CO emissions of quite small values were detected at

Table 2
Major operating variables and gaseous emissions (in 6% O_2 flue gas) measured in the experimental tests of the 150 MW boiler fired with Thai lignite at various values of excess air [5]

Variable	Nomenclature	Unit	Run no.				
			1	2	3	4	5
Excess oxygen[a]	O_2	%vol.	1.14	2.30	3.42	4.20	5.05
Electric power output of the unit	$\dot{W}_e$	MW	149.9	150.5	151.4	149.8	150.2
Superheated steam flow rate	$\dot{m}_{sh}$	kg/s	120.7	121.5	120.6	119.1	121.0
Superheated steam temperature	t_{sh}	°C	524.8	526.1	532.0	532.2	525.6
Reheated steam flow rate	$\dot{m}_{rh}$	kg/s	110.1	109.5	110.1	109.3	110.1
Inlet reheated steam temperature	$t_{rh,1}$	°C	336.8	336.2	341.0	341.0	333.7
Outlet reheated steam temperature	$t_{rh,2}$	°C	529.9	531.6	536.4	534.6	529.6
Temperature of feed water	t_{fw}	°C	232.3	232.2	232.2	232.6	232.2
Temperature of the waste flue gas	θ_{wg}	°C	168	164	164	163	161
SO_2 concentration in the flue gas[b]	SO_2	ppm	76	57	56	50	70
NO_x concentration in the flue gas	NO_x	ppm	257	283	308	316	325
CO concentration in the flue gas	CO	ppm	172	16	–	–	–
Carbon content in fly ash	C_{fa}	%wt	0.29	0.17	0.19	0.23	0.28

[a] At the economizer exit.
[b] Downstream from the FGD unit.

the low values of excess oxygen; nevertheless, these CO concentrations were used as the input value for determining q_3.

3.1.3. Boiler thermal efficiency and environmental performance

Two optimization methods were applied with the aim of determining of the optimum excess air ratio for the selected boiler: (1) the conventional (or heat-loss) method, with the objective function given by Eq. (1), and (2) the cost-based method accounting for the “external” costs only, with the objective function given by Eq. (4), ignoring, however, the SO_3 and soot emissions. While the NO_x, SO_2 and CO emissions were found experimentally, the rate of the CO_2 emission was calculated by Eq. (12).

To avoid the influence of fuel quality and boiler load fluctuations on the optimization process by the cost-based method, the cost items were calculated as the specific (i.e. related to the actual electric power output) characteristics. Such an approach was applied with the use of the specific fuel consumption and emissions, kg/MW h, in the relevant models and these specific characteristics were found based on the corresponding mass flow rates (in kg/s) and $\dot{W}_e$ (in MW, as given in Table 2).

Table 3 shows the fuel feed rate together with characteristics of thermal efficiency and environmental performance (as specific emissions) of the boiler versus excess air ratio at the sampling point, i.e. at the boiler economizer exit. The data on the boiler emissions indicated significant environmental impacts by CO_2 and NO_x emissions discharged from this boiler unit when firing Thai lignite.

3.1.4. Optimized excess air ratio

In the cost-based optimization, the specific “external” costs for the relevant pollutants were assumed from Ref. [13]: $P_{NO_x} = 7.495$ US\$/kg; $P_{SO_2} = 1.719$ US\$/kg; $P_{CO} = 0.992$ US\$/kg, whereas $P_{CO2} = 0.03$ US\$/kg selected by Ref. [12] was used in the study.

Table 3
Excess-air-dependent heat losses, boiler gross efficiency and rated fuel consumption as well as specific emissions for the 150 MW boiler fired with Thai lignite at various values of the excess air ratio [5]

Variable	Unit	Run no.				
		1	2	3	4	5
α	–	1.06	1.12	1.20	1.25	1.32
q_2[a]	%	8.04	8.08	8.35	8.80	8.96
q_3	%	0.09	0.01	–	–	–
q_4	%	0.19	0.11	0.13	0.14	0.18
η_b	%	91.21	91.33	91.04	90.59	90.39
$\dot{m}_f$	kg/s	35.35	34.93	34.94	36.00	37.16
m_f	kg/MW h	849.0	835.5	830.8	865.2	890.6
m_{NO_x}[b]	kg/MW h	1.816	1.996	2.159	2.247	2.326
m_{SO_2}	kg/MW h	0.767	0.575	0.561	0.508	0.716
m_{CO}	kg/MW h	0.741	0.069	–	–	–
m_{CO_2}	kg/MW h	1029	1014	1016	1050	1051

[a] Found for the excess air ratios at the air heater (boiler) exit.
[b] Downstream from the FGD units.

The optimization results obtained by the two methods are depicted in Fig. 1. Despite a relatively small value of P_{CO_2}, the CO_2 contribution to the total "external" costs was found to be predominant (63–65%). The NO_x share in these costs seemed to be noticeable (29–35%, for various α) whereas the SO_2 cost contributions were considered to be the minor ones.

As seen in Fig. 1, the optimized excess air ratio found by the heat-loss method was 1.11–1.12 whereas it was slightly lower (1.09—1.10) if being determined by the cost-based method. The step in the excess air ratio from the set point (1.28) to the value located in the range between the above-optimized values (say, 1.11) would result in the significant reduction of the environmental impact (of the cost equivalent of about 3.3 US$/MW h) done by the boiler with the simultaneous improvement in the boiler thermal efficiency (by some 0.8%). Thus, for the working period of about 7000 h/year, the annual reduction, or saving, in the "external" costs of about 3,500,000 US$/year per this 150 MW boiler unit operated at full load could be achieved from switching the boiler to firing Thai lignite at $\alpha = 1.11$.

3.2. Firing fuel oil/gas in a 90 t/h industrial boiler

3.2.1. Boiler design characteristics and fuel properties

A D-shape refinery boiler firing fuel oil/gas was the focus of this experimental study [6,27]. The boiler was designed to supply 90 t/h of superheated steam at 80 bar and 470 °C to different refinery processes.

However, this boiler has been mostly operated at reduced loads. The actual loads, basically of 65–80% rated boiler capacity, depended on the current steam demand for the refinery processes. A single value of excess oxygen at the economizer outlet (namely, 2%

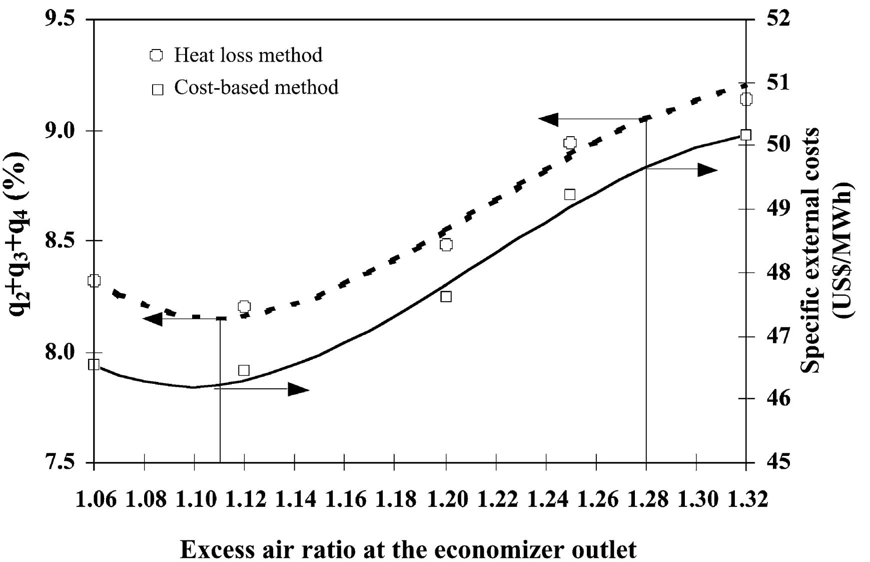

Fig. 1. Total excess-air-dependent heat losses and specific "external" costs for the 150 MW boiler firing Thai lignite (the minimums of these dependencies correspond to the optimum excess air ratios) [5].

Table 4
Properties (%wt) and LHV (MJ/kg) of fuel oil ("as-received" basis) used in the experimental study on the 90 t/h refinery boiler [6]

W^r	A^r	C^r	H^r	O^r	N^r	S^r	LHV
0.10	0.00	86.60	12.50	0.54	0.06	0.20	42.20

O_2, corresponding to the excess air ratio of about 1.1) was, however, specified for all the boiler loads. Because of the supercharged draft system, the excess air ratio along the gas path in the boiler was unchanged (except for the air heater), and the excess air ratio at the furnace exit was, therefore, equal to that at the sampling point. No flue gas recirculation was applied on this boiler, which resulted in high-temperature conditions in the flame core, specifically at high boiler loads.

Though the boiler was fired with fuel oil/gas mixture, the boiler fuel consumption and some other relevant characteristics were determined for the boiler as fired by fuel oil only. This assumption was made because the energy share by gaseous fuel (refinery byproduct) accounted for less than 20% and also taking into consideration the fluctuations in fuel gas analysis. The representative fuel analysis of fuel oil used in this study is shown in Table 4.

3.2.2. Thermal and environmental performance of the boiler at reduced loads

The main objective of the study was to determine the optimum excess air ratios for the range of typical boiler loads. To achieve this goal, the boiler was tested at three loads, of 84, 70 and 64 t/h (or 93.3, 77.8 and 71.1% of the rated boiler capacity, respectively). In the test runs, the emission concentrations were measured in the flue gas at the sampling point (i.e. at the boiler economizer outlet) for various excess oxygen values.

As an illustration, the data related to the boiler thermal efficiency as well as the fuel consumption for the boiler operated at 70 t/h load for different excess air ratios at the sampling point are shown in Table 5. All the characteristics given in Table 5 were quantified based on the actual operating variables (steam properties, flue gas temperature, etc.) collected during the tests. As found from experimental data, the effects of both the load and excess air ratio on the heat losses and gross thermal efficiency (consequently, on the fuel consumption) of the boiler were rather noticeable.

Table 5
Heat losses, boiler gross efficiency and fuel consumption for the 90 t/h industrial boiler operated at 77.8% load for various excess air ratios at the economizer exit [27]

Variable	Unit	Run no.							
		1	2	3	4	5	6	7	8
α	–	1.02	1.04	1.06	1.08	1.15	1.20	1.25	1.30
q_2[a]	%	7.18	7.28	7.38	7.48	7.84	8.09	8.34	8.59
q_3	%	0.74	0.36	0.04	–	–	–	–	–
q_5	%	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
η_b	%	91.14	91.42	91.63	91.58	91.22	90.97	90.72	90.47
$\dot{m}_f$	kg/s	1.205	1.201	1.198	1.199	1.202	1.205	1.208	1.211

[a] Found for the excess air ratios at the air heater (boiler) exit.

In the experimental tests, the CO emissions were found at low values of excess oxygen, and the CO concentrations in the flue gas were obviously depended on the boiler load. Furthermore, α_{cr} were determined to be 1.06, 1.09 and 1.14 for the boiler loads of 84, 70 and 64 t/h, respectively, demonstrating the apparent effect of the load on the critical excess air ratio.

As indicated in Ref. [6], for the boiler load of 84 t/h, thermal NO was partially involved in NO_x formation; meanwhile, prompt NO was the major contribution to the total NO_x emissions for the lower loads (70 and 64 t/h) when firing this fuel with very small fuel-N. The NO_x emissions were found to depend on both the boiler load and excess oxygen. For the 84, 70 and 64 t/h loads, the NO_x emissions (in 6% O_2 dry gas) were in the ranges of 261–319, 186–216, and 148–200 ppm, respectively, at various excess air ratios.

The SO_2 profiles were independent of the excess air ratio and the boiler load. The SO_2 concentrations (in 6% O_2 dry gas) of about 30, 65–90 and 46–58 ppm for the loads of 84, 70 and 64 t/h, respectively, were solely influenced by the fluctuations in fuel-sulfur during the tests.

3.2.3. Optimized and "compromise" excess air ratios

For the above boiler loads, the excess air optimization was carried out with the use of the objective function given by Eq. (5), ignoring the SO_3 and soot emissions. The environmental cost items involved in the excess air optimization were calculated for the specific "external" costs $P_{SO_2} = 3.0$ US$/kg and $P_{CO_2} = 0.03$ US$/kg (assumed by Ref. [12]) as well as $P_{NO_x} = 7.495$ US$/kg and $P_{CO} = 0.992$ US$/kg (assumed by Ref. [13]). The fuel costs were estimated assuming $P_f = 0.136$ US$/kg, as provided by the refinery, and taking into account that $\dot{m}_{f,a}$ in Eq. (5) was equal to $\dot{m}_f$ (because $q_4 = 0$). Fig. 2 shows the fuel costs along with the relevant environmental costs for the same, as in Table 5, boiler load for the two distinct excess air ratios.

In Fig. 3, the dependencies of the total costs on the excess oxygen concentration at the sampling point are shown for the studied boiler operating at the 84, 70 and 64 t/h loads. As seen in Fig. 3, the minimum of the total costs occurred at the O_2 concentrations of about

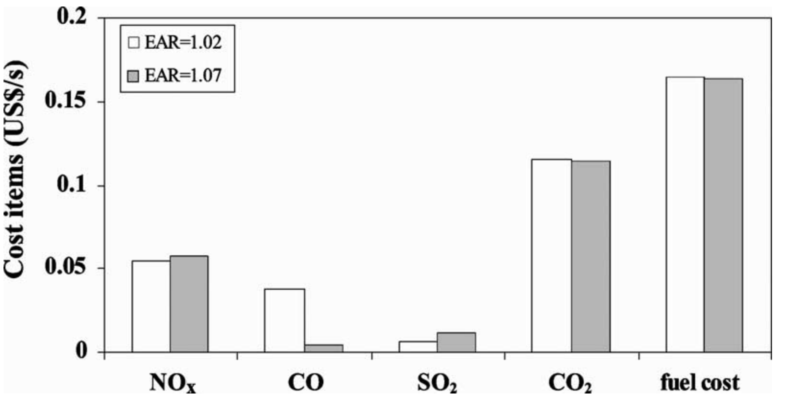

Fig. 2. Break down of the fuel and environmental costs incorporated into the total costs for the 90 t/h refinery boiler operated at 77.8% load for two different values of excess air ratio (EAR) [27].

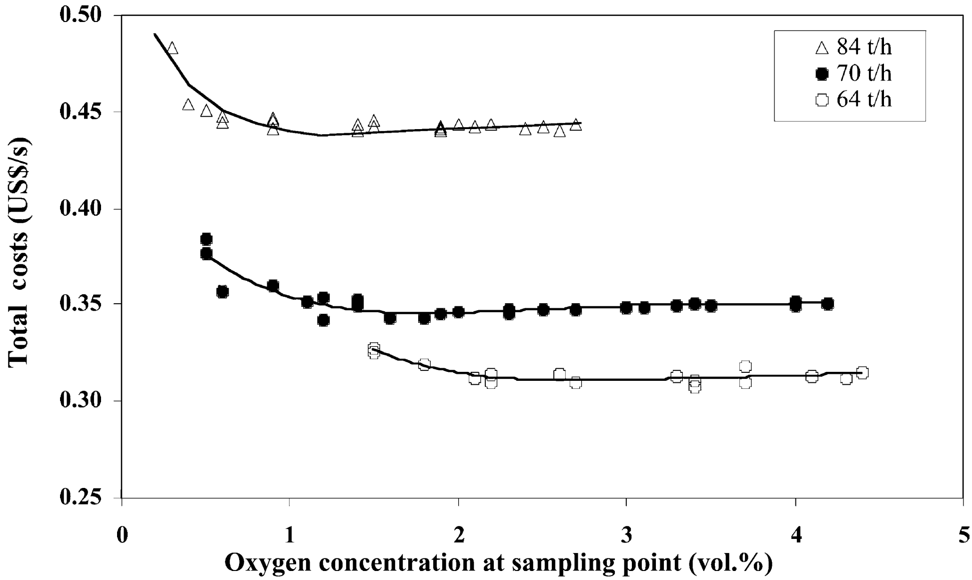

Fig. 3. Total costs versus oxygen concentration for the 90 t/h refinery boiler operated at reduced loads of 84, 70 and 64 t/h [6].

1.2, 1.8 and 2.7, corresponding to the optimum excess air ratios of 1.06, 1.09 and 1.15, respectively.

Meanwhile, the experimental results indicated the fluctuations in the O_2 concentration around the set point, with SD of about $\pm 0.2\%$. However, to avoid the risk of soot formation, the excess oxygen concentrations in the flue gas should be maintained at the value of about 1.5% O_2 or higher [8]. Thus, for high loads (i.e. greater than 82% of the boiler design capacity), the specified value of 1.5% O_2 (corresponding to the excess air ratio of 1.08) seemed to be the “compromise” set point for this operating variable, whereas the optimized excess air ratios should be specified for the lower boiler loads.

As followed from the cost analysis for the 84 t/h load, switching the boiler to operation at the “compromise” excess air ratio of 1.08 could provide the total costs savings of about 47,300 US$/year per boiler unit through the reduction in both the fuel and environmental costs. Meanwhile, the annual total costs saving of about 189,200 US$/year per boiler unit could be achieved for the 64 t/h boiler load with the implementation of the optimized excess air ratio of 1.15 instead of the currently used set point. Likewise, the benefits from the implementation of the optimized excess air ratios can be determined for all of the operated boiler loads.

3.3. Firing fuel oil in a 310 MW utility boiler

3.3.1. Essential input

The fuel oil-fired utility boiler of a 310 MW capacity was selected for this computational study [16]. For 100% loading, the boiler produced about 1000 t/h of

Table 6
Properties (%wt) and LHV (MJ/kg) of medium-sulfur fuel oil ("as-received" basis) used in the computational study on the 310 MW boiler [16]

W^r	A^r	C^r	H^r	O^r	N^r	S^r	LHV
0.30	0.00	86.35	11.19	0.00	0.86	1.30	40.93

superheated steam at 540 °C and 160 bar. The reheated steam of 860 t/h at 40 bar was returned into the boiler to increase its temperature to 540 °C.

The tangentially fired furnace with the burners arranged at four corners was characterized by the heat release rate (per unit cross-sectional area) of about 6.27 MW/m^2 for the full load of the boiler firing fuel oil with the LHV of 40.93 MJ/kg. The properties of this fuel are shown in Table 6. For the boiler loads of 80–100%, the excess air ratio was specified at the constant value of 1.08 (design characteristic).

The recirculation of about 10% of the total flue gas volume (extracted at the boiler economizer exit) was used on the 100% loaded boiler in order to maintain the temperatures of the superheated and reheated steam as well as for the NO_x reduction. At the reduced boiler loads, the volume of the recirculated flue gas remained at the same value, thus, leading to the corresponding increased volume fractions of the flue gas recirculation.

3.3.2. Predicted fuel and environmental costs

The excess air optimization was carried out for the two boiler loads (100% and 80%), i.e. for the limits of the boiler load range within which the excess air (ratio) was maintained at the constant value. The cost-based method, comprising both fuel and "external" costs, with the objective function given by Eq. (5), was applied in this computational case study. For both boiler loads, the independent variable, i.e. excess air ratio, varied in the computations in the range of 1.02–1.14.

As an illustration, the predicted heat losses, as well as the gross thermal efficiency and fuel consumption are shown in Table 7 for this boiler operated at 100% load and different excess air ratios. For ensuring higher computational accuracy, the q_2 represented in Table 7 was calculated taking into account actual temperatures of the waste gas obtained in

Table 7
Heat losses, gross efficiency and fuel consumption for the 310 MW fuel oil-fired boiler operated at 100% load for various excess air ratios at the furnace outlet [16]

Variable	Unit	Excess air ratio at the boiler furnace outlet						
		1.02	1.04	1.06	1.08	1.10	1.12	1.14
q_2[a]	%	6.536	6.584	6.630	6.674	6.718	6.759	6.800
q_3	%	0.0635	0.0159					
q_4	%	0.0095	0.0024					
q_5	%	0.2	0.2	0.2	0.2	0.2	0.2	0.2
η_b	%	93.191	93.216	93.170	93.126	93.082	93.041	93.000
$\dot{m}_f$	kg/s	19.595	19.584	19.589	19.594	19.599	19.603	19.606

[a] Found for the excess air ratios at the air heater (boiler) exit.

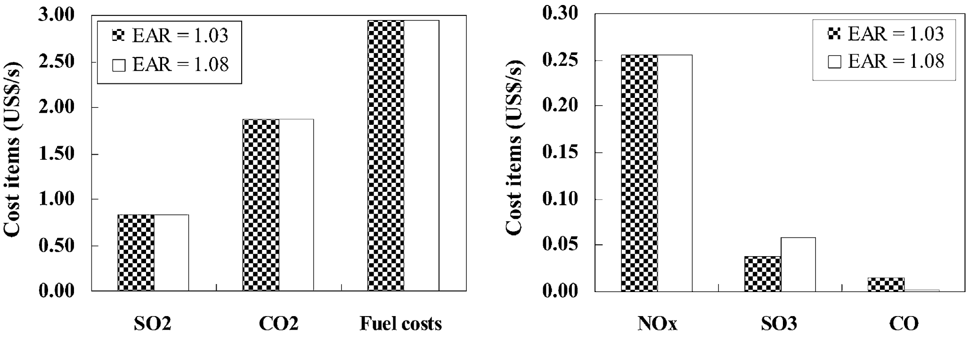

Fig. 4. Break down of the fuel and environmental costs incorporated into the total costs for the 310 MW fuel oil-fired boiler operating at 100% load for two different values of excess air ratio (EAR) [16].

the performance tests as well as actual excess air ratios at the waste gas correlated with the load-dependent excess air ratio at the furnace outlet. The q_3 was determined based on Eq. (36) accounting for the CO [found by Eq. (32)] with the use of the experimentally estimated α_{cr} (for each load) and $A = 50$. Meanwhile, the heat loss with unburned carbon was quantified via its correlation with the heat loss owing to incomplete combustion to be $q_4 = 0.15\ q_3$ [16]. As seen in Table 7, the boiler thermal efficiency attained the maximum at the excess air ratio of about 1.04. The fuel costs were estimated based on the boiler fuel consumption and the fuel oil price $P_f = 0.15$ US$/kg.

The emission rates for the NO_x, SO_3, SO_2, CO_2 and CO were predicted by the above emission models for the corresponding values of the excess air ratio (as given in Table 7). In computations of the environmental, costs, the specific “external” costs were assumed by Refs. [12,13] as: $P_{NO_x} = 2.4$ US$/kg, $P_{SO_3} = 3.0$ US$/*kg*, $P_{SO_2} = 1.72$ US$/*kg*, $P_{CO_2} = 0.03$ US$/*kg* and $P_{CO} = 0.99$ US$/kg.

Fig. 4 illustrates various environmental costs along with the fuel costs for the same, as in Table 7, boiler load for two distinct excess air ratios. As seen in Fig. 4, the major contribution to the total costs was made by the fuel costs, as well as by CO_2 (despite the relatively low value of P_{CO_2}) and SO_2. The cost impacts by NO_x, SO_3 and CO were apparently the minor ones. Similar data and effects were also found for the 80% boiler load.

3.3.3. Optimized and “compromise” excess air ratios

In Fig. 5, the dependencies of the total costs on the furnace excess air ratio are shown for the two boiler loads (100 and 80%) within which the excess air ratio was normally maintained at the constant value. As seen in Fig. 5, both curves possess a cost minimum corresponding to the optimum excess air ratio: 1.04 for the 100% load and 1.055 for the 80% load.

However, these values were in the vicinity of the α_{cr} for both loads (1.04 and 1.045, respectively). Taking into consideration fluctuations of the excess air ratio with the estimated standard deviation $\Delta\alpha = \pm(0.006–0.013)$ in the actual boiler operation, a “compromise” excess air ratio of 1.06 was recommended as the specified value (instead of

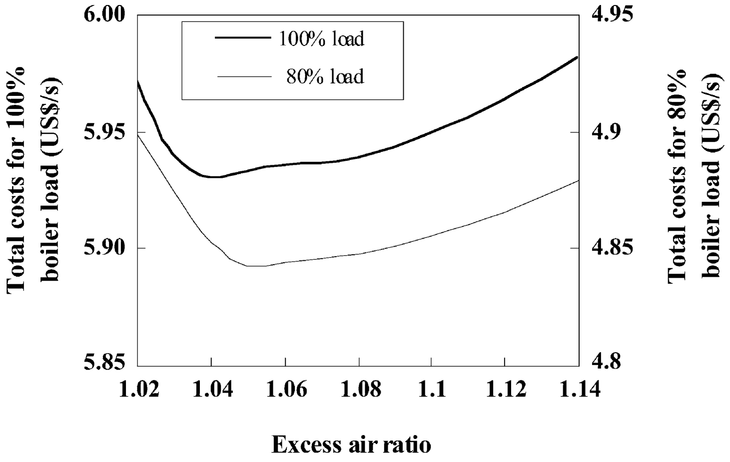

Fig. 5. Total costs versus excess air ratio for 100 and 80% loads of the 310 MW boiler firing fuel oil [16].

1.08 currently used) for this operating variable in order to avoid elevated soot formation in the 80–100% loaded boiler.

As may be seen in Fig. 5, the estimated difference in the total costs at the excess air ratios of 1.08 and 1.06 was approximately 0.01 US$/s for both loads. Thus, the potential saving of about 250,000 US$/year (assuming the boiler operation in the load range of 80–100%, during 7000 h/year) could be expected, provided that the excess air ratio were maintained at the optimum value. As followed from the cost analysis, this benefit could be achieved through both fuel and environmental cost savings.

4. Conclusions

The cost-based method has been successfully applied in the optimization of the excess of combustion air for utility and industrial boilers fired with fossil fuel of different types. The review of the published literature has shown the method applicability in both experimental study and theoretical analysis. The method has also demonstrated its flexibility with respect to the fuel type as well as to the unit capacity and load. Different objective functions can be applied for the optimization depending upon the desired goals. Switching the combustion excess air to the optimized value ensures significant reduction of the total boiler costs associated with the fuel consumption (“internal” costs) and environmental impact (“external” costs) for the particular boiler. However, the selected value of excess air should ensure the combustion process with the minimized soot formation, particularly when firing fuel oil/gas. In such cases, taking into consideration this operational constraint, the “compromise” excess air should be applied on the boiler (instead of the optimized one), providing, nevertheless, the noticeable fuel cost saving with simultaneous reduction of the environmental impact by the boiler unit.

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